Diffraction at HERA and the TEVATRON

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Representing the CDF, D0, H1 and ZEUS collaborations

1. **Definitions**
2. **Kinematics and Experimental Signatures**
3. **Inclusive processes:**
   - Properties of $\mathbf{F_2^{I\!P}}(\beta\,, Q^2\,)$
   - HERA-TEVATRON Data and Test of Factorization
4. **Exclusive processes:**
   - Vector Meson production
   - DVCS

6. **Conclusions**

HERA beams:

$\mathbf{e^{\pm}}$ → ← **p**

27.5 GeV **820 GeV**

e-p center of mass energy: $\sqrt{s_{ep}} = \mathbf{300\ GeV}$

Two general purpose detectors, H1 and ZEUS, are placed on the HERA ring.

TEVATRON beams:

p → ← $\bar{p}$

900 GeV **900 GeV**

p-p center of mass energy: $\sqrt{s_{ep}} = \mathbf{1800\ GeV}$

Two general purpose detectors, CDF and D0, are placed on the TEVATRON ring.

WHY DIFFRACTION?

because POMERONS are everywhere!!!

You can find pomerons in:

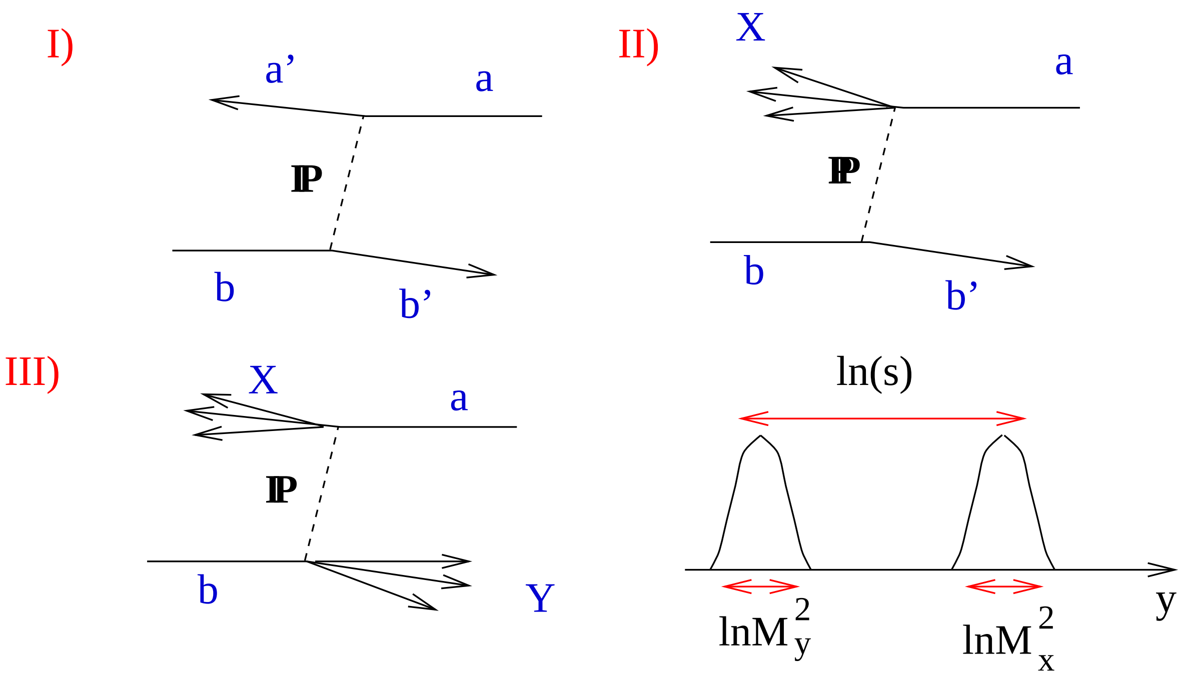
- Total cross section
- Deep Inelastic Scattering
- Between Jets
- Vector meson production
- Regge theory and Pure QCD
- Many conferences

Diffractive events are defined as those events mediated by pomeron exchange

Definition by description

Even if diffraction is responsible for a large part of the cross section (elastic scattering), very little is known on the nature of the pomeron.

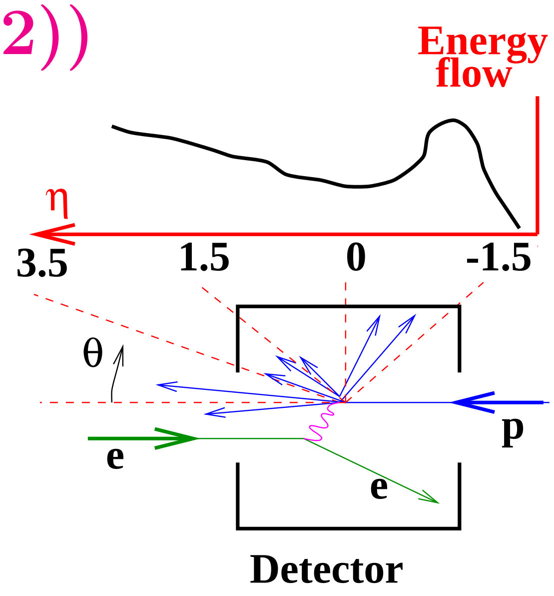
- No quantum numbers are exchanged
- Low p_t final states
- M_x and M_y are independent
  $\Rightarrow$ rapidity gap



Pomeron exchange represents a generic term for long range QCD reaction needed to explain the rise of the total cross section

Experimental signature: Rapidity gap

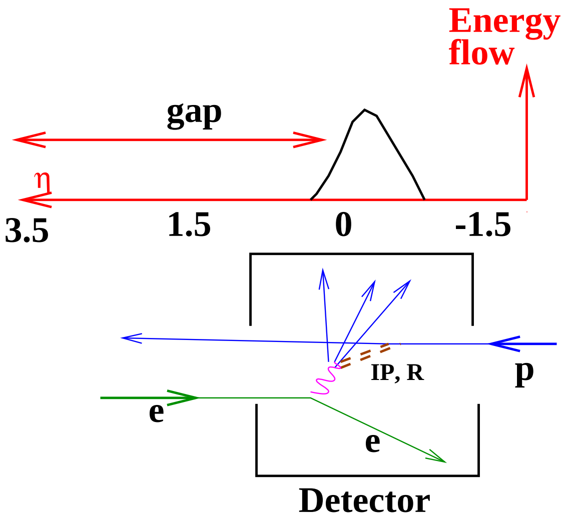
Define: η = -ln(tan(θ/2))



Probability to have a gap:

"Standard" event:

$$\underline{\mathbf{p}(\Delta\eta) \sim \mathbf{e}^{-\Delta\eta}}$$



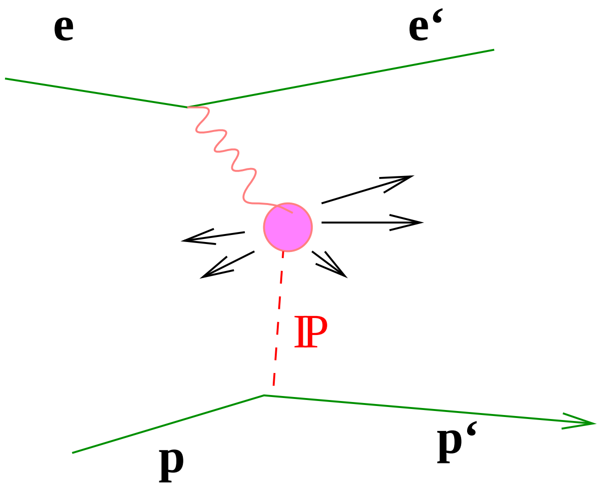
"Diffractive" event :

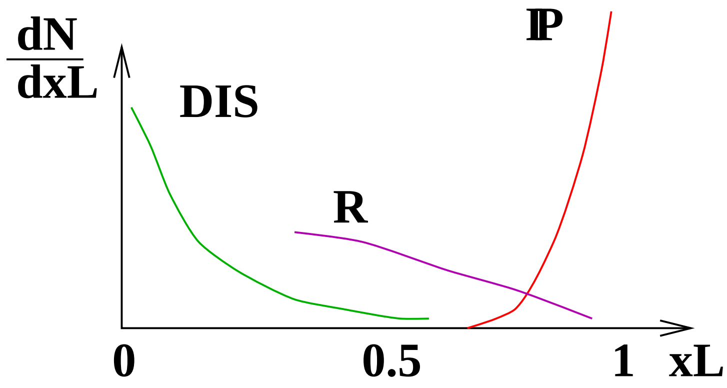
$$\mathbf{p}(\Delta\eta) \sim \mathbf{e}^{-2(\alpha(0)-1)\Delta\eta} \sim$$

$$\underline{\mathbf{p}(\Delta\eta) \sim \mathbf{e}^{0}}$$

$\Rightarrow$ Diffractive events are those which lead to a large rapidity gap in final state phase space and are not exponentially suppressed as a function of gap width.

Experimental signature:
Leading proton in the final state:





- High fraction of original longitudinal momentum:

  For pomeron exchange: $x_L = \frac{p_z'}{p_z} \sim 1.$

  For non pomeron exchange: $x_L = \frac{p_z'}{p_z} < 1.$

- Low transverse momentum:

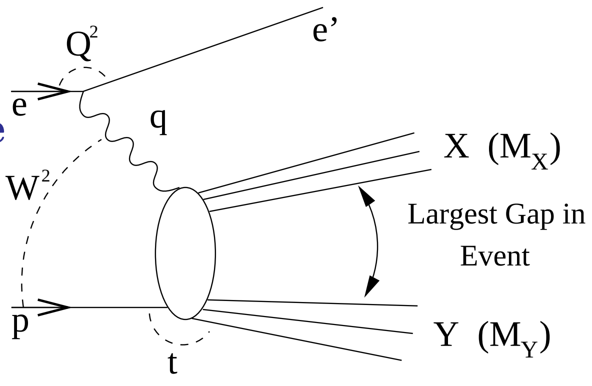
$$\frac{dN}{dp_\perp^2} \sim e^{-b \cdot p_\perp^2}$$

with $b = 5\text{-}15\ \mathrm{GeV}^{-2}$

Selection Methods:

Rapidity gap:

H1, DO, CDF, and ZEUS use a selection method based on a visible gap of particle in pseudorapidity. The event is accepted if the largest visible gap is larger than 2-4 unit of pseudorapidity.



Ln M_X^2:

Diffractive sample/cross section defined as excess contribution in the ln M_X^2 distribution above the exponential fall-off of the non-diffractive peak

$$\frac{d\mathcal{N}}{dM_X^2} \sim \frac{1}{M_X^2} \Longrightarrow \frac{d\mathcal{N}}{d\ \ln M_X^2} = \text{const}$$

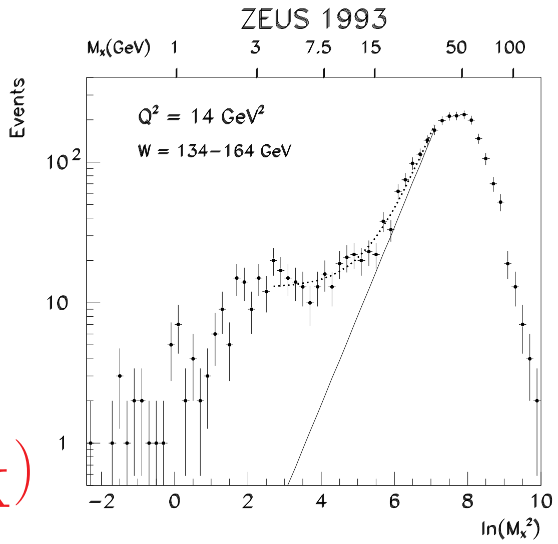
while for non-diffractive scattering:

$$\frac{d\mathcal{N}}{d\ \ln M_X^2} = \exp(\mathbf{b}\ \ln \mathbf{M_X^2})$$

(uncorrelated particle emission)

then:

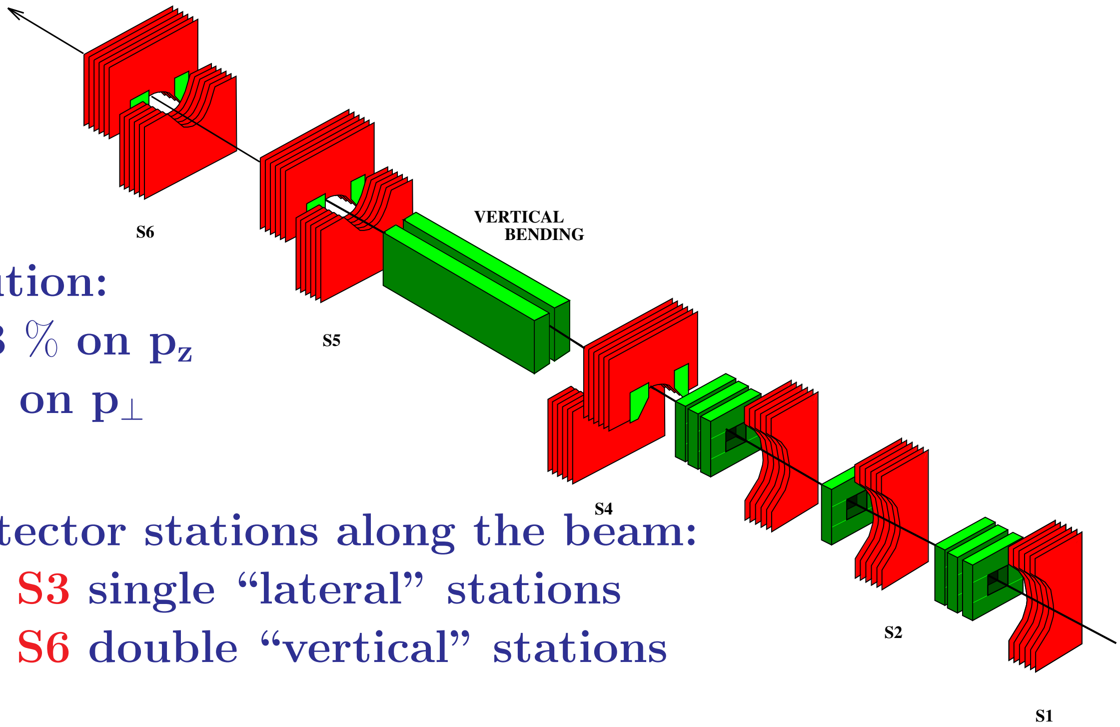
$$\frac{d\mathcal{N}}{d\ \ln M_X^2} = \mathbf{D} + \mathbf{c}\ \exp(\mathbf{b}\ \ln \mathbf{M_X^2})$$



Selection Method: Leading Proton

The ZEUS and CDF collaborations have a "Leading Proton Spectrometer" to directly measure the scattered proton.

LPS acceptance: $0.6 < x_L < 1.0$ and $0 < p_\perp^2 < 1$ GeV^2



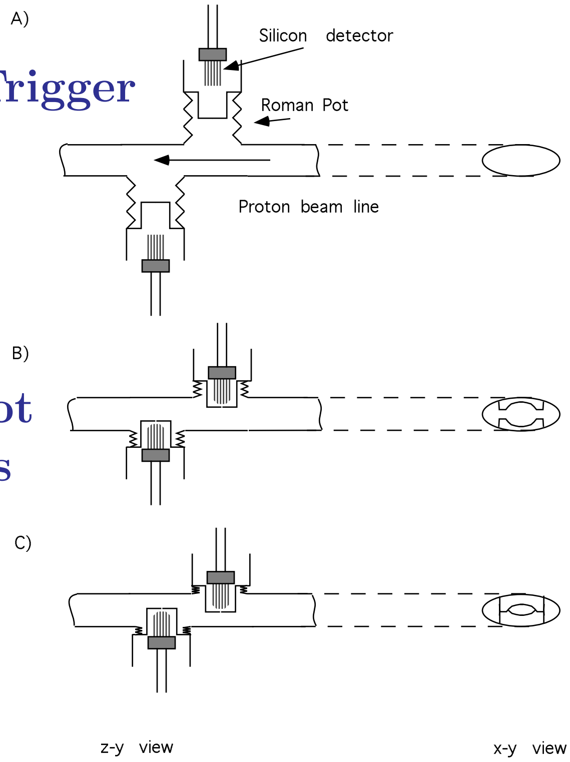
- Resolution:
  - $\simeq 0.3\ \%$ on p_z
  - $\simeq 3\ \%$ on $p_\perp$

- Six detector stations along the beam:
  S1 $\longrightarrow$ S3 single "lateral" stations
  S4 $\longrightarrow$ S6 double "vertical" stations

- Collected Luminosity:
  0.9 pb^{-1} in 1994
  2.5 pb^{-1} in 1995. Installed LPS Trigger
  4.0 pb^{-1} in 1996

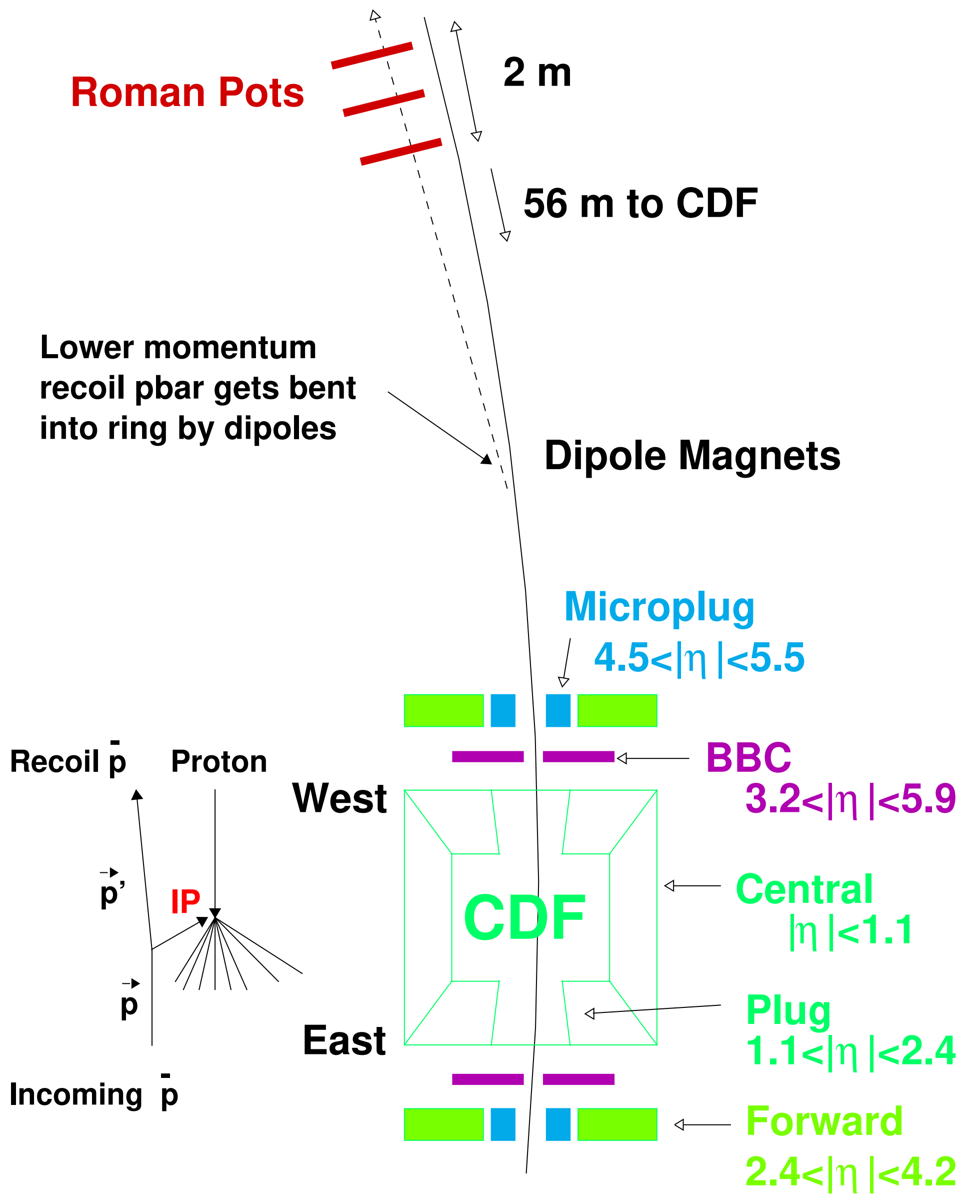
- Detector operations using Roman pots

- Six μstrip silicon detectors per pot
  - three different strip orientations $(0^o, +45^o, -45^o)$
  pitch: 115μm $\rightarrow 0^o \sqrt{2}\mu$m $\rightarrow \pm 45^o$
  - cut out to follow the 10σ beam profile



CDF Proton Spectrometer

Diffractive Dijets with Leading Antiproton



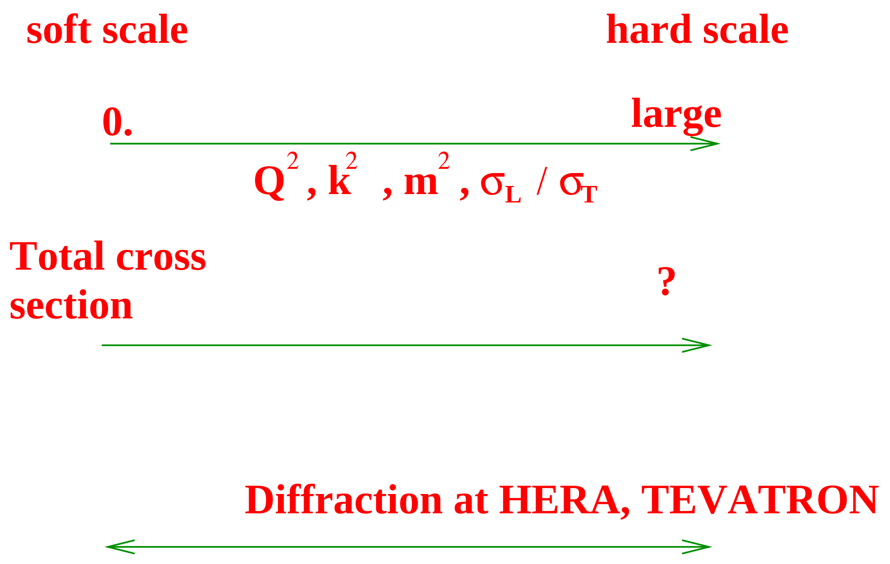
$$\sigma_{x,y} = 100\mu m \quad \sigma_\xi = 0.001 \quad \sigma_t = 0.07\mathrm{GeV}^2$$

How do we get to know a Pomeron?
Hard and soft scales in Diffraction

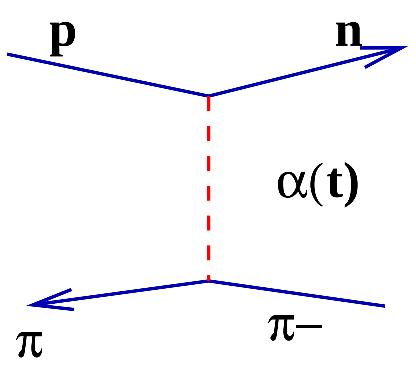
We have a problem:
The large majority of diffractive events are soft, i.e. they do not have a hard scale in the interaction
To study the partonic nature of diffraction we need to isolate the subsample of diffractive events which has a hard scale.

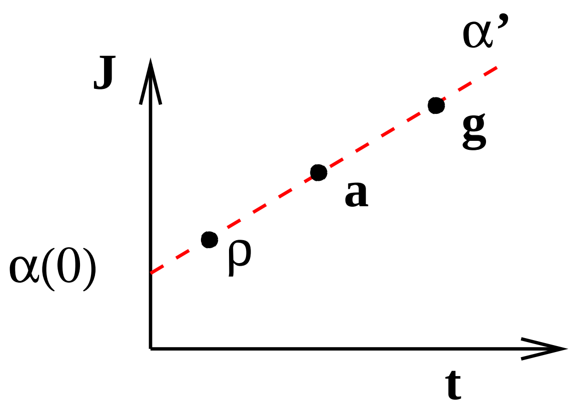
- The total cross section is a soft process, the scale is p_t
- Jet production in diffractive events has a hard scale (p_t)
- Diffractive DIS has a hard scale (Q^2),
- Diffractive Heavy Flavour has a hard scale (m_q),
- Diffractive production of Vector meson might have a hard scale (m_V).

→ To understand Diffraction it is neccessary to study both soft and hard events and the transition between the two regimes.



Models of Diffraction:
Soft Physics and QCD

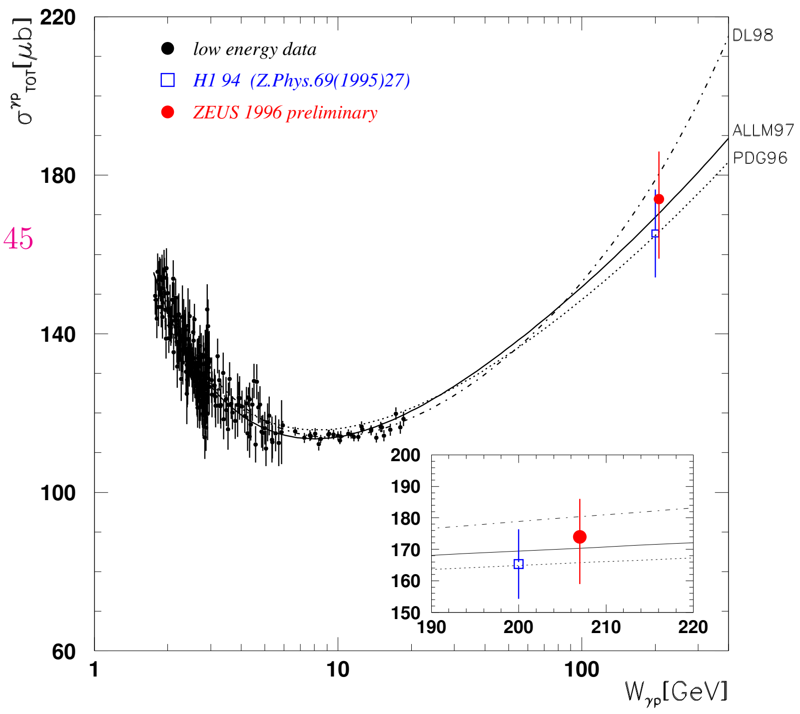




1) Diffractive physics is traditionally classified as a soft phenomena. There is a rich phenomenology (Regge Theory) which works well within the regime of diffraction without a hard scale

- Scattering is mediated by the exchange of a "trajectory" $\alpha(\mathbf{t}) = \alpha(\mathbf{0}) + \alpha^{'}\mathbf{t}$, ex: $\pi^{-}p \rightarrow \pi^{o}n$ mediated by the ρ trajectory: $\rho,\ a_2,\ g$
- Two main trajectories: Pomeron and Reggeon,
- The cross section goes like: $\sigma_{tot} \propto s^{\alpha_k(0)-1}$

Fit to all hadronic data:
$\sigma^{\mathbf{tot}}(\mathbf{hp}) = X \cdot s^{0.08} + Y \cdot s^{-0.45}$



Models of Diffraction: Soft Physics and QCD

2) Diffractive physics with a hard scale at HERA and TEVATRON has opened a wide range of QCD tests Simplified picture (for HERA):

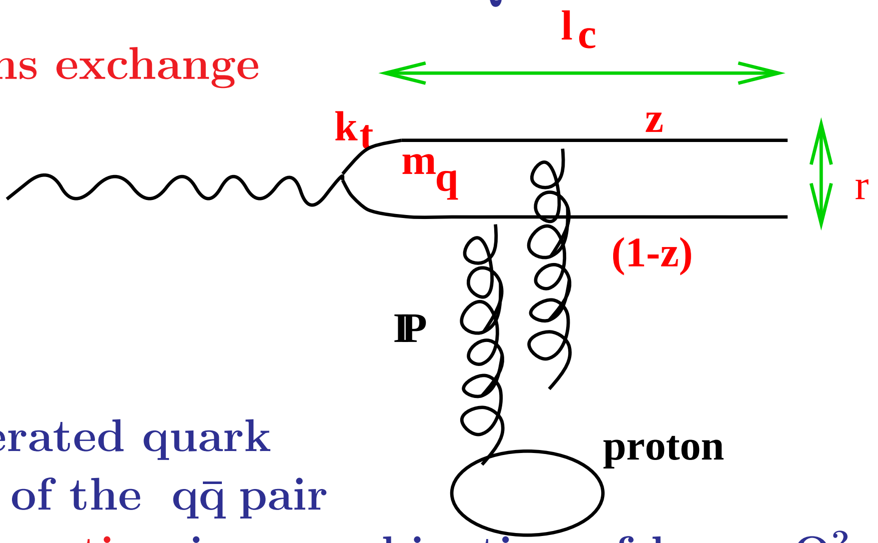
- Think in the proton rest frame $\rightarrow E_\gamma \sim 5-40$ TeV.
- The photon fluctuates, $\gamma^* \rightarrow q\bar{q}$, $\gamma^* \rightarrow q\bar{q}g$, upstream the proton target and collapses into the final state well after the interaction.
- The interaction is modelled in terms of color dipoles.
- These fluctuations are described in QCD

$\Rightarrow$ Pomeron = 2-gluons exchange

fluctuation length:

$l_c = \frac{1}{2m_p * x_{bj}} > 100\mathrm{fm}$

$r_\perp$ Radius of $q\bar{q}$



m_q Mass of the generated quark

$k_\perp, z$ T,L momentum of the $q\bar{q}$ pair

The scale of the interaction is a combination of $k_\perp$, z, Q^2, m_q and can be expressed as:

$$\frac{1}{r_\perp^2} = k_\perp^2 \frac{Q^2 + M_x^2}{M_x^2} + m_q^2$$

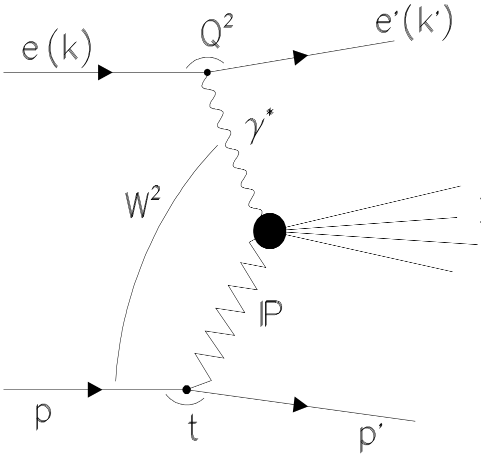
Note: There are slightly different versions of $r_\perp$ available

Small $r_\perp \Longrightarrow$ hard scale $\Longrightarrow$ QCD prediction

Large $r_\perp \Longrightarrow$ soft scale $\Longrightarrow$ Modelling

Diffraction: Kinematics

HERA case, but it works for TEVATRON too...



One more vertex !

To standard DIS variables add:

$\mathbf{t = (P - P')^2}$ **Momentum transfer at the proton vertex**

$\mathbf{M_X^2 = (q + I\!P)^2}$ $I\!P - \gamma$ **invariant mass squared**

$\beta = \frac{\mathbf{Q^2}}{\mathbf{2(P-P')\cdot q}} = \frac{\mathbf{x}}{x_{I\!P}} = \frac{\mathbf{Q^2}}{\mathbf{M_X^2+Q^2-t}}$ $\frac{M_X^2}{Q^2} >> 1 \;\; \beta \sim 0.$,

$\frac{M_X^2}{Q^2} << 1 \;\; \beta \sim 1.$

Two variables describe the longitudinal momentum lost by the proton in the interaction:

$x_{I\!P} = \frac{\mathbf{(P-P')\cdot q}}{\mathbf{P\cdot q}} = \frac{\mathbf{M_X^2+Q^2-t}}{\mathbf{W^2+Q^2-M_p^2}}$ **Calorimeter**

$\mathbf{x_L} = \frac{\mathbf{p_z'}}{\mathbf{p_z}}$ **Proton spectrometer**

$\mathbf{x_L = 1} - x_{I\!P} \sim \mathbf{1}.$

Inclusive Diffraction

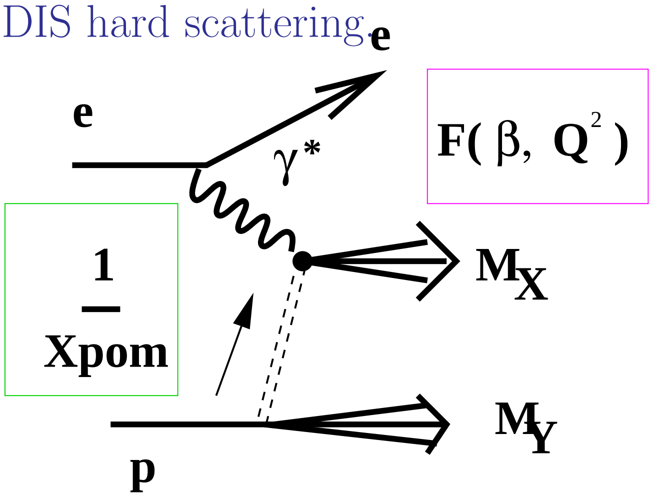
Define:

$$\frac{d^4\sigma}{dQ^2 d\beta dx_{I\!P} dt} = \frac{2\pi\alpha^2}{Q^4\beta}[1+(1-y)^2]F_2^{D(4)}(Q^2,\beta,x_{I\!P},t)$$

Factorization holds for diffractive DIS:

$$F_2^{D(4)}(Q^2,\beta,x_{I\!P},t) = \Sigma_i \int^{x_{I\!P}} dz f_{i/p}^{D}(x_{I\!P},t,z,\mu^2)\hat{F}_i(x/z,Q^2/\mu)$$

where f_i are the parton densities and $\hat{F}_i$ the DIS hard scattering.

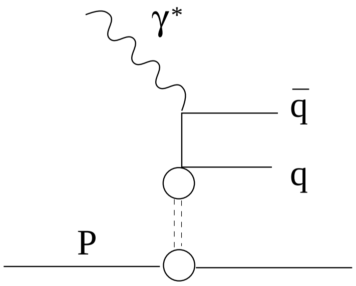


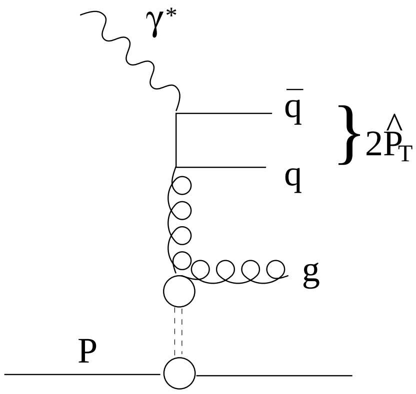
If postulate Regge Factorization:

$F_2^{D(4)}(Q^2,\beta,x_{I\!P},t) = f_{I\!P/p}(x_{I\!P},t)F_2^{I\!P}(\beta,Q^2)$

Both $q\bar{q}$ and $q\bar{q}g$ neccessary:

Quark Dominated **Gluon Dominated**





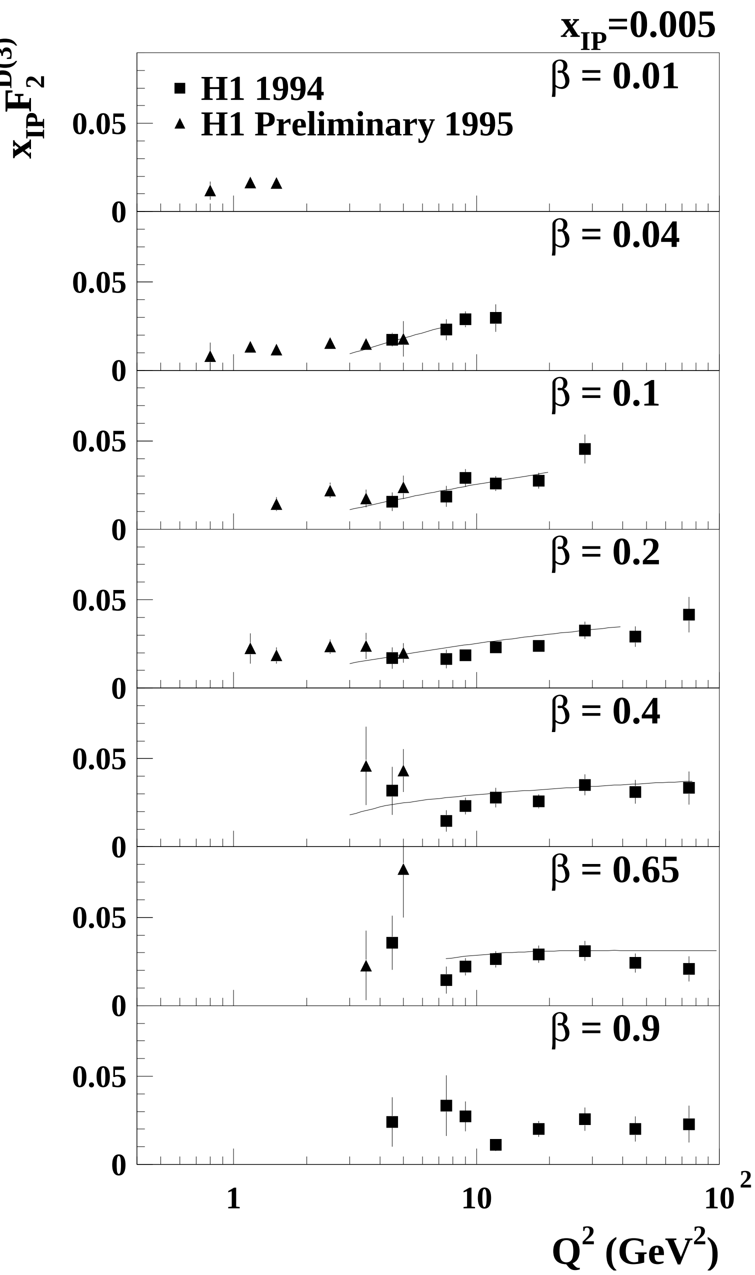
Tools to study partonic contents:

QCD fit, High $p_\perp$ jets, Charm production, Energy flow

Note: no factorization for $p\bar{p}$

QCD analysis of $\tilde{F}_2^{I\!P}(Q^2, \beta)$ (H1)

- Consider light quark flavor singlet $(u + \bar{u} + d + \bar{d} + s + \bar{s})$ + gluon
- Parameterize at $Q_0^2 = 2.5\,\mathrm{GeV}^2$: $x_{i/I\!P} f_i(x_{i/I\!P}) = A_i x_{i/I\!P}^{B_i} (1 - x_{i/I\!P})^{C_i}$
- Solve DGLAP evolution equations to evolve parton densities to higher Q^2 and fit A_i, B_i, C_i to data
- Charm included via photon–gluon fusion
- No momentum sum rule imposed



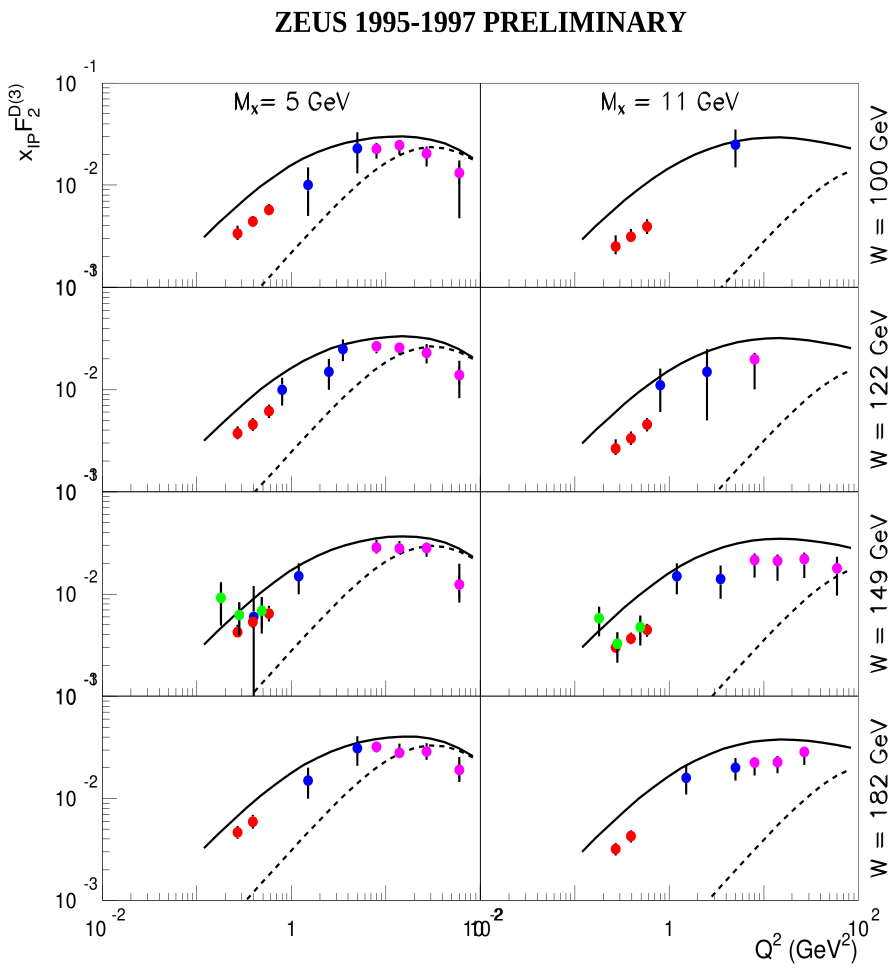
Very different from the proton:
- Large gluon content
- Sea-like scaling at large β

$\Rightarrow$ Scaling violation at high β implies a strong gluon component

The Partonic Structure

At low Q^2 $F_2^D(x,Q^2)$ grows like $F_2(x,Q^2)$, the rising behaviour is not trivial

Measurement of $x_{I\!P}F_2^{D(3)}$ vs Q^2



ZEUS BPC 96-97 PRELIMINARY (Method I)

ZEUS LPS 95 PRELIMINARY (Method II)

H1 shifted vertex 95 PRELIMINARY

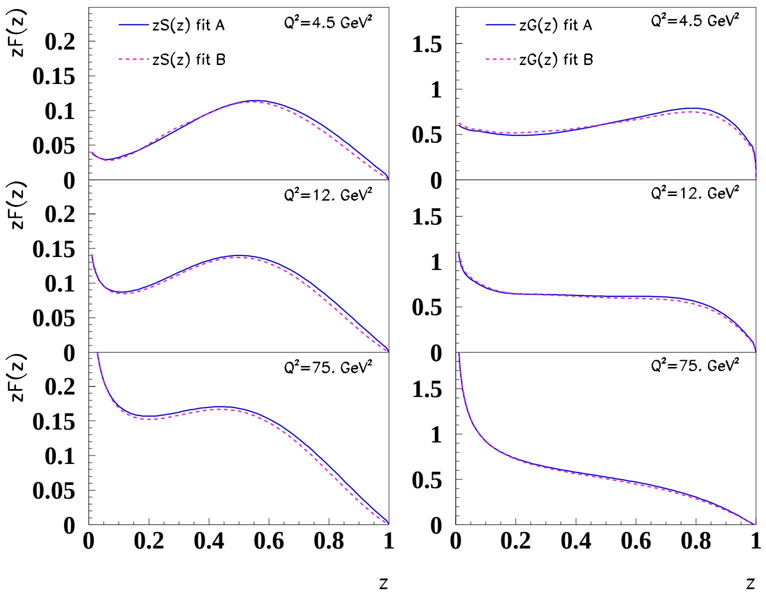
ZEUS DIS 94

Curves by K. Golec-Biernat (private comunication)

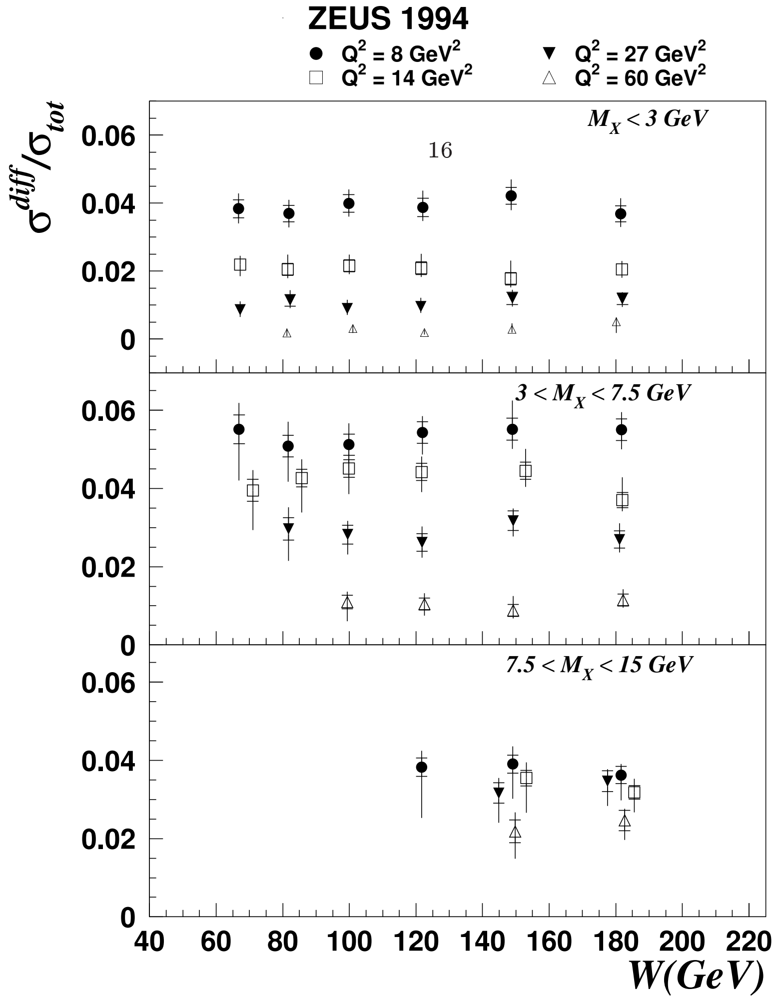
Important contribution of $q\bar{q}g$ at low Q^2?

The Partonic Structure:

QCD fits of all F_2^D data



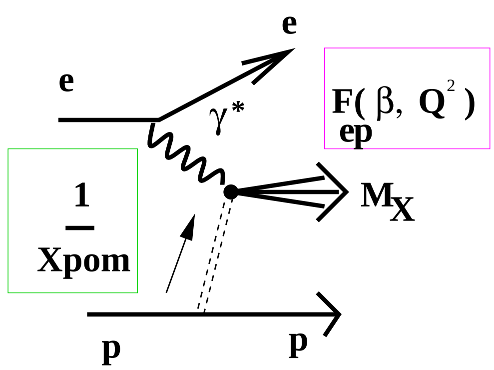
QCD Fit: Diffractive F_2 vs Non-Diffractive F_2



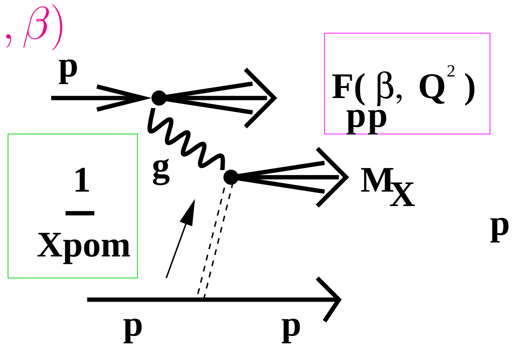
The Partonic Structure of the Pomeron

Test of Factorization:

- HERA vs TEVATRON,
- HARD vs SOFT scale



$$\mathbf{F_2^{D(3)}}(\mathbf{Q^2}, \beta, x_{I\!P}) \sim \left(\frac{1}{x_{I\!P}}\right)^{\mathbf{a}} \cdot \mathbf{F_2^{I\!P}}(\mathbf{Q^2}, \beta)$$



- The Pomeron Structure Function can be studied both in ep and pp collision using the same techniques used for the standard proton structure function

Factorization implies:

$\left(\frac{1}{x_{I\!P}}\right)^{\mathbf{a}}$	**pomeron flux**
$\mathbf{F_2^{I\!P}}(\mathbf{Q^2}, \beta)$	**pomeron structure function**

The pomeron flux and Pomeron structure function are independent of scale and projectile.

Diffractive Dijets with Leading Antiproton, CDF

Physics Motivation:

1. Measure the diffractive structure function
   $F_{jj}^D(\beta, \xi, Q^2, t)$

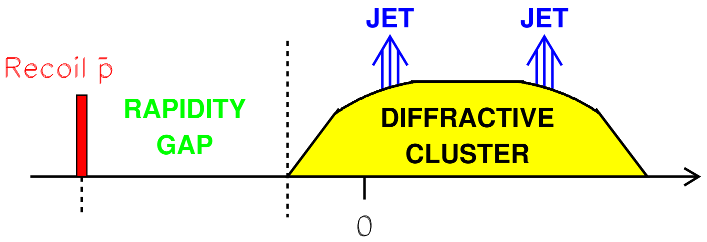
$$\left(\begin{array}{c} F_{jj}^D(x, \xi, Q^2, t) = x \left[g^D(x, \xi, Q^2, t) + \frac{4}{9} q^D(x, \xi, Q^2, t) \right] \\ F_{jj}^D(x, \xi, Q^2, t) \longrightarrow F_{jj}^D(\beta, \xi, Q^2, t) \end{array} \right)$$

$$\frac{d^5(p\bar{p} \to pjjX)}{dx_p\, d\beta\, d\xi\, dt\, dp_T^2} = \frac{F_{jj}(x_p, Q^2)}{x_p} \frac{F_{jj}^D(\beta, \xi, Q^2, t)}{\beta} \frac{d\hat{\sigma}_{gg \to gg}}{dp_T^2}$$

2. Test QCD factorization by comparing $F_{jj}^D(\beta, \xi, Q^2, t)$ with expectation from the measurements of diffractive DIS at HERA

3. Test Regge factorization

$$F_{jj}^D(\beta, \xi, Q^2, t) \stackrel{?}{=} f_{I\!P/p}(\xi, t)\; F_{jj}^{I\!P}(\beta, Q^2)$$

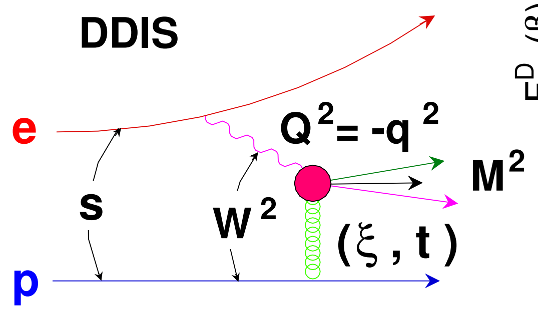


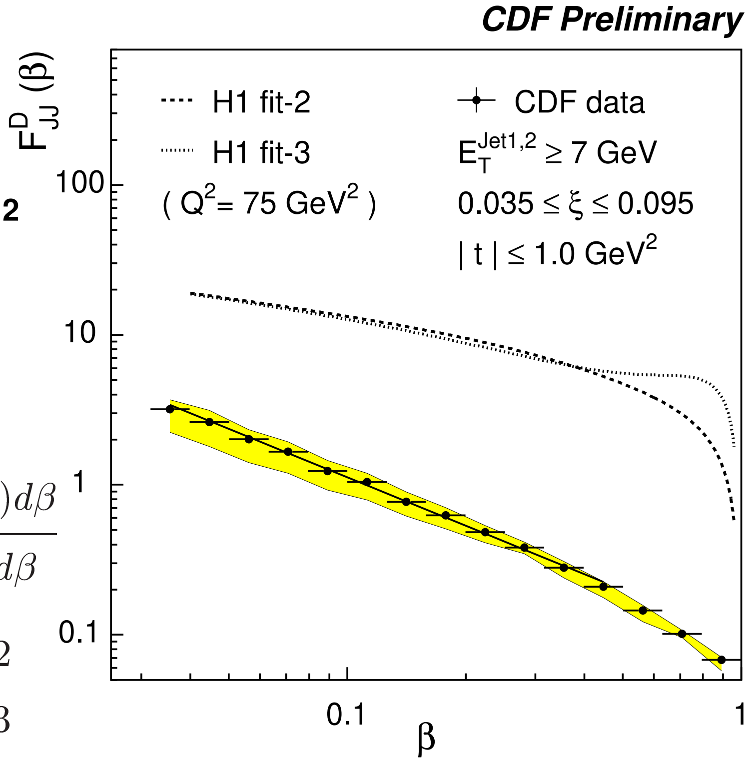
$$x_{\bar{p}} = p_{g,q}/p_{\bar{p}}, \qquad x_p = p_{g,q}/p_p$$

$$\xi = 1 - x_F = p_{I\!P}/p_{\bar{p}}, \qquad \beta = p_{g,q}/p_{I\!P}$$

TEVATRON-HERA comparison

Comparison with expectations from H1 results





$$D = \frac{\int_{\log\beta=-1.4}^{\log\beta=0} F^D_{jj}(\beta; CDF)d\beta}{\int_{\log\beta=-1.4}^{\log\beta=0} F^D_{jj}(\beta; H1)d\beta}$$

$$= \begin{cases} 0.06 \pm 0.02 & \text{for fit-2} \\ 0.05 \pm 0.02 & \text{for fit-3} \end{cases}$$

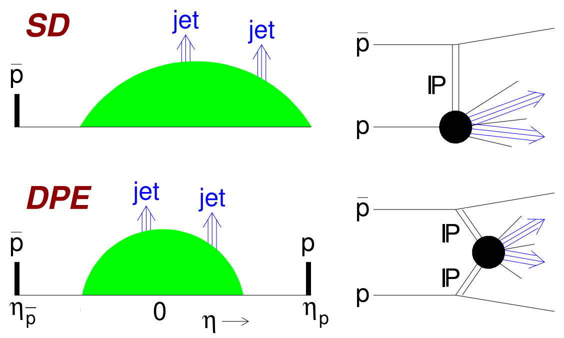
CDF normalization uncertainty $= \pm 26$ %

Factorization test TEVATRON - HERA:
Measure F^D in $p\bar{p}$ collision and compare it to HERA F^D from ep collision

- **Discrepancy in shape and magnitude**

Double - Single Pomeron Exchange

Test of Factorization



$$\sigma_{ND} = \sigma_0 F(x_p, Q^2)\, F(x_{\bar{p}}, Q^2)$$

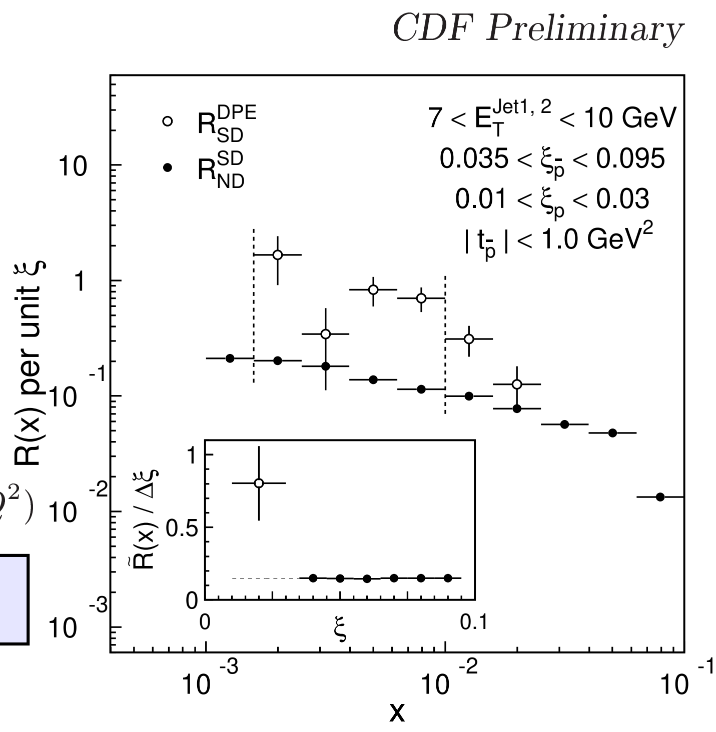
$$\sigma_{SD} = \sigma_0 F(x_p, Q^2)\, F^D(x_{\bar{p}}, \xi, Q^2)$$

$$\sigma_{DPE} = \sigma_0 F^D(x_p, \xi, Q^2)\, F^D(x_{\bar{p}}, \xi, Q^2)$$

$$\boxed{\langle R_{\frac{SD}{ND}} \rangle / \langle R_{\frac{DPE}{SD}} \rangle = 0.19 \pm 0.07}$$

$(10^{-2.8} < x < 10^{-2})$

Breakdown of Factorization



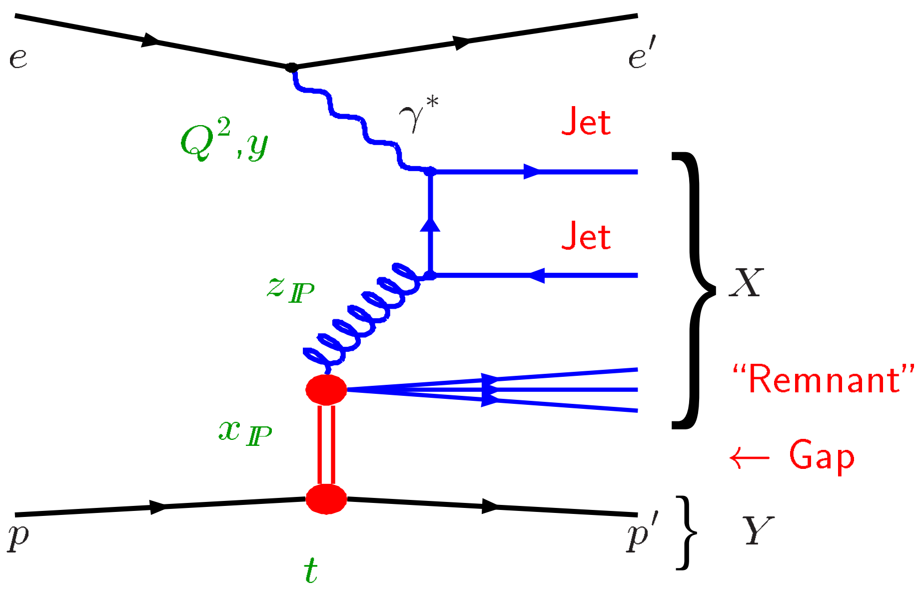
Factorization test at TEVATRON:
Measure the ratio single pomeron / double pomeron exchange

- **Found factorization breaking within the TEVATRON data**

2-3 jet Production in Diffractive Events

Kinematics

Viewed in terms of a resolved (i.e. partonic) "Pomeron" model:



Q^2, y → DIS variables

$x_{I\!P} \approx \frac{Q^2+M_X^2-t}{Q^2+W^2-M_p^2}$ → longit. momentum fraction of colourless exchange w.r.t. p

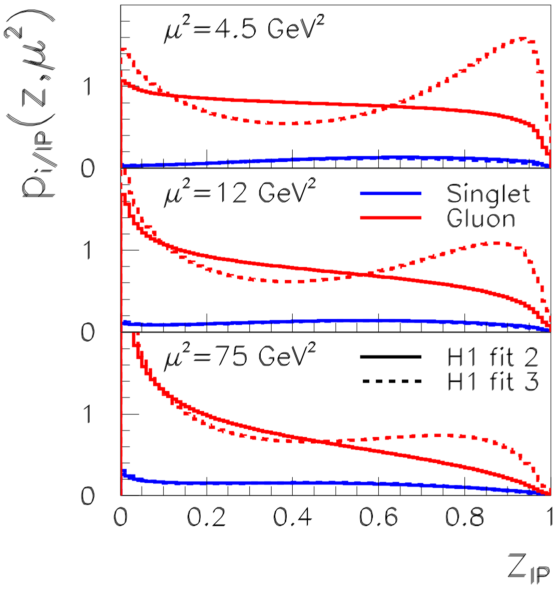
$z_{I\!P} \approx \frac{Q^2+M_{12}^2}{Q^2+M_X^2}$ → momentum fraction of exchange coupling to γ^*

$|t|$ → $(\text{momentum transfer})^2$ at p vertex

Dijet Studies: partonic content

H1 QCD fits to inclusive $F_2^{D(3)}$

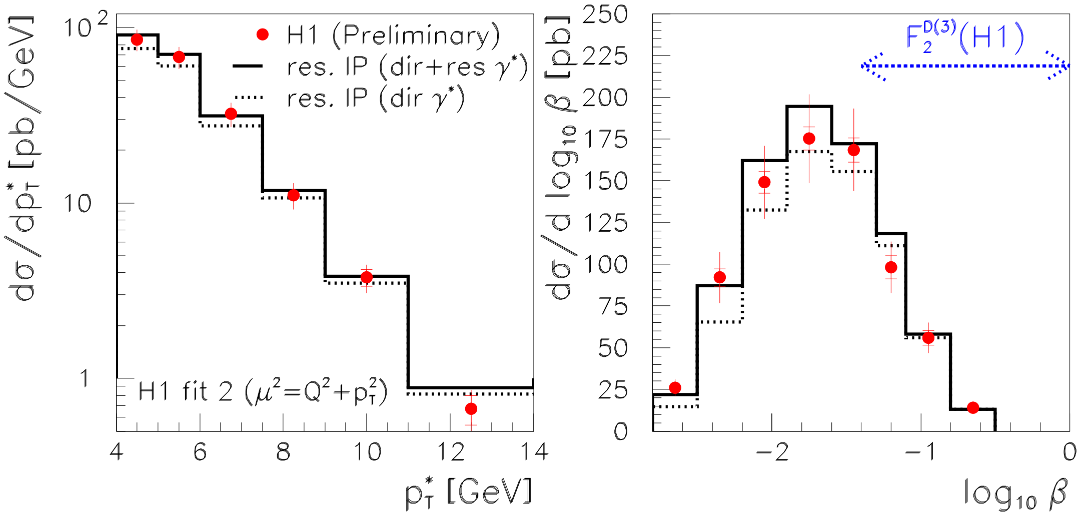
- Regge Factorisation:
  $\sigma \sim f_{I\!P/p}(x_{I\!P}, t)\ F_2^{I\!P}(z, \mu^2)\ |M|^2\ (+subl.\ exch.)$



Partonic "Pomeron":
$F_2^{I\!P} = \sum_i e_i^2\ q_{i/I\!P}(z, \mu^2)$

$\rightarrow f_{q/I\!P}(z, \mu^2)$
direct!

$\rightarrow f_{g/I\!P}(z, \mu^2)$
indirect (scaling viol.)!



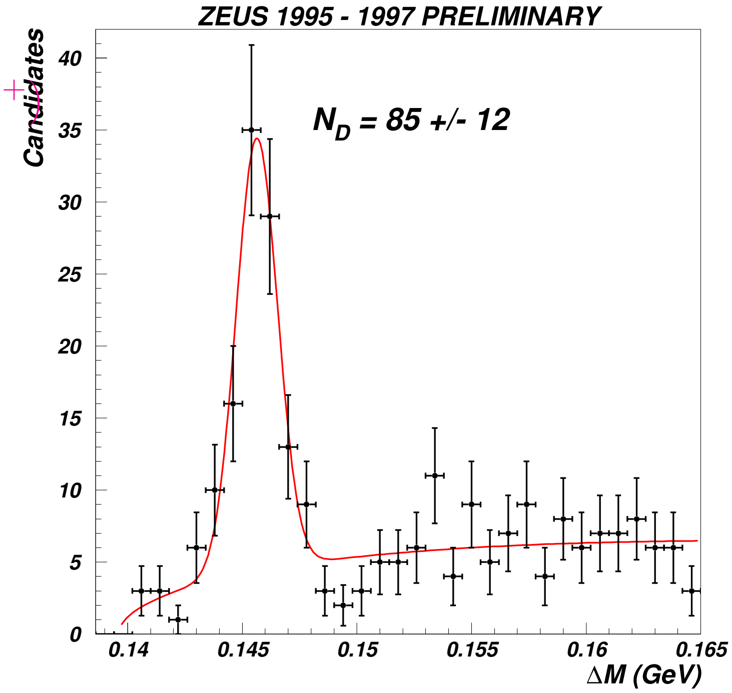
- Applying results of $F_2^{D(3)}$ QCD fits to jets works very well!
- β range very different!

Diffractive Production of D^*

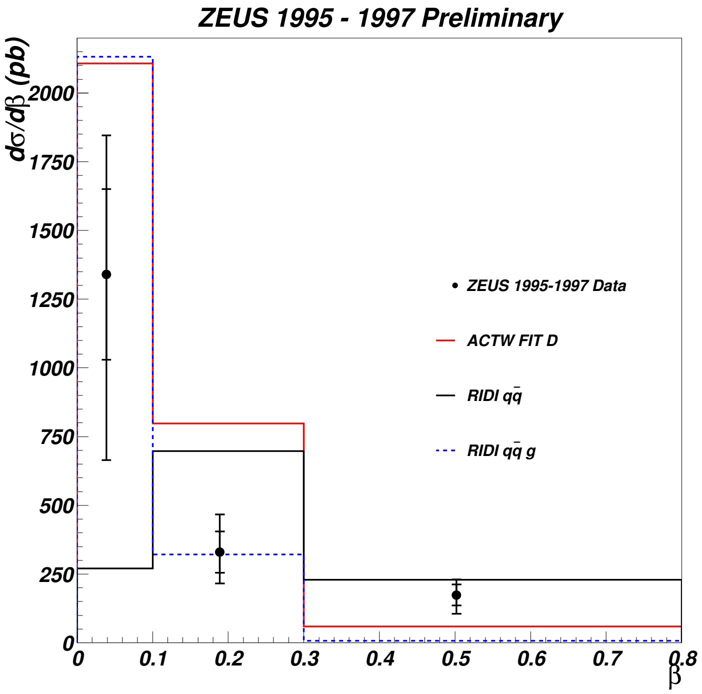
Cross section evaluated from decay channel:

$D^{*+} \rightarrow D^0 \pi^+_{slow} \rightarrow (K^- \pi^+) \pi^+_{slow}$
$\Delta M = M(K^- \pi^+ \pi^+_{slow}) - M(K^- \pi^+)$

- $1.5 < p_t(D^*) < 8$ **GeV**
- $1 < Q^2 < 450$ **Ge**V^2
- $abs(\eta(D^*)) < 1.5$ **Ge**V^2
- $x_{I\!P}$¡ **0.015**



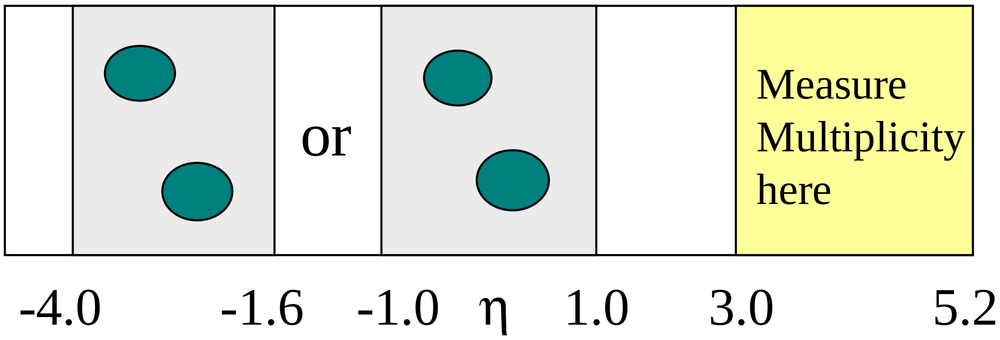
Diffractive charm production sheds light on the gluons:
Need of $q\bar{q}g$ component!



Diffraction in $p\bar{p}$

Hard Single Diffraction Study at DØ

(hep-ex/9912061)



Measure Gap Fraction :

(diffractive dijet events / all dijet events)

@ 1800 and 630 GeV

⋆ Forward Jet Trigger

two 12 GeV Jets $|\eta| > 1.6$

⋆ Inclusive Jet Trigger

two 15(12) GeV Jets $|\eta| < 1.0$

Study SD Characteristics :

⋆ Single Veto Trigger @ 1800 and 630 GeV

a rapidity gap on one side

two 15(12) GeV Jets

Diffraction in $p\bar{p}$

DØ Single Diffractive Results

DØ Preliminary

		Gap Fraction (%)			
Sample	Data	Hard Gluon	Flat Gluon	Soft Gluon	Quark
($s(\beta) \propto$)		$\beta(1-\beta)$	const.	$(1-\beta)^5$	$\beta(1-\beta)$
1800 Fwd	$\boxed{0.65 \pm 0.04}$	2.2 ± 0.3	2.2 ± 0.3	1.4 ± 0.2	0.79 ± 0.12
1800 Cent	0.22 ± 0.05	2.5 ± 0.4	3.5 ± 0.5	0.05 ± 0.01	0.49 ± 0.06
630 Fwd	1.19 ± 0.08	3.9 ± 0.9	3.1 ± 0.8	1.9 ± 0.4	2.2 ± 0.5
630 Cent	0.90 ± 0.06	5.2 ± 0.7	6.3 ± 0.9	0.14 ± 0.04	1.6 ± 0.2
		Ratio of Gap Fraction			
630/1800 Fwd	1.8 ± 0.2	1.7 ± 0.4	1.4 ± 0.3	1.4 ± 0.3	2.7 ± 0.6
630/1800 Cent	4.1 ± 0.9	2.1 ± 0.4	1.8 ± 0.3	3.1 ± 1.1	3.2 ± 0.5
1800 Fwd/Cent	3.0 ± 0.7	0.88 ± 0.18	0.64 ± 0.12	$30. \pm 8.$	1.6 ± 0.3
630 Fwd/Cent	1.3 ± 0.1	0.75 ± 0.16	0.48 ± 0.12	$13. \pm 4.$	1.4 ± 0.3

- Data: $R[\frac{SD}{ND}] = \begin{cases} 0.65 \pm 0.04\ \% & \text{DØ} \\ 0.75 \pm 0.10\ \% & \text{CDF} \end{cases}$
- To describe DØ + CDF data, MC requires
  1. soft + hard structure of gluon and quark
  2. reduced cross section

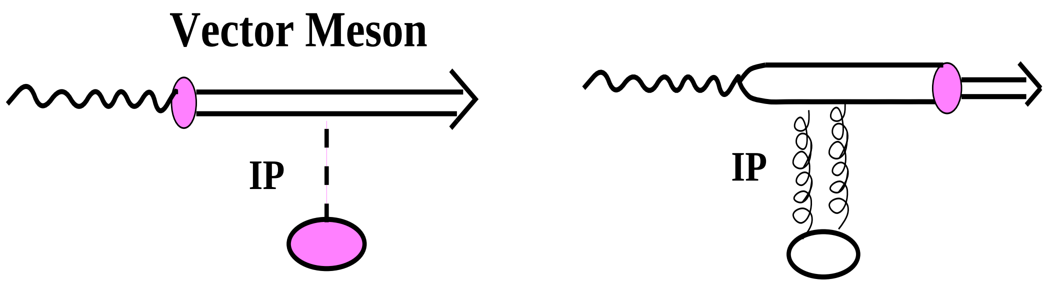
HERA: Diffractive DIS = 10% All DIS events
TEVATRON: Gap fraction = 1% All events

Summary on Inclusive Diffraction

- Data favor a significant gluon component in the Pomeron: results from QCD fit, jet production,charm cross section and hadronic energy flow support this hypothesis
- Both factorizable models and pure pQCD describe the data well
- Differences between TEVATRON and HERA show factorization breaking
  - HERA and TEVATRON F_2^D are different both in shape and normalization,
  - HERA: Diffractive DIS = 10% Non Diffractive DIS
  - TEVATRON: Diffractive $W, b\bar{b}\ \ dijet = 1\%$ Non Diffractive
- The factor of 20 remains to be clarified

Vector Meson production: pQCD and soft physics

- **VDM + Regge theory:** the $\gamma \to$ V transition happens before the interaction and then the vector meson scatters hadronically with the proton
- **QCD inspired:** the $q\bar{q}$ pair interacts with the target first and then the meson is formed

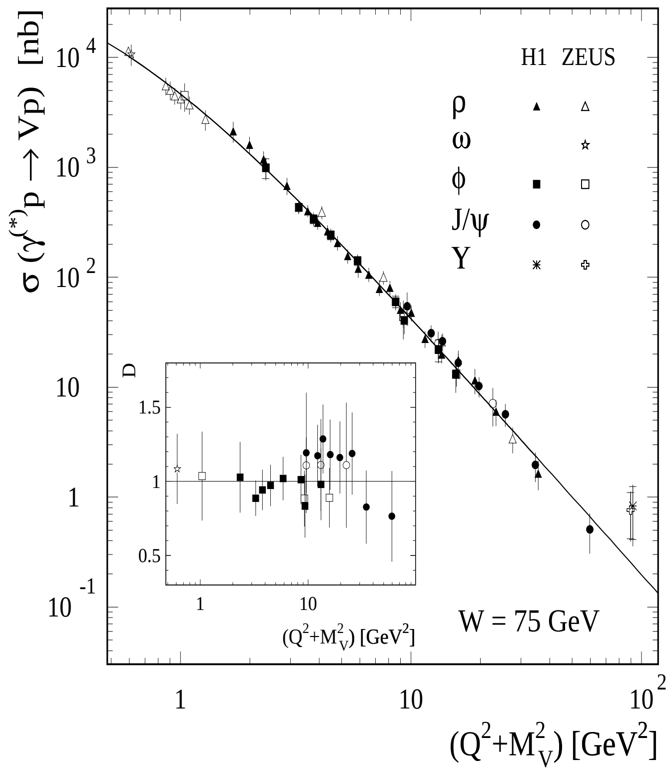


$$\sigma_{ep\to Vp} \propto \sigma(\gamma^* \to q\bar{q}) \;\; \sigma_{q\bar{q}p} \;\; \sigma(q\bar{q} \to V)$$

- VDM works well when the scale is soft
- QCD works well when the scale is hard

The scale is set by a combination of Q^2, t, M_V^2:

$$\bar{Q}^2 = 0.2(M_V^2 + Q^2 + |t|)$$



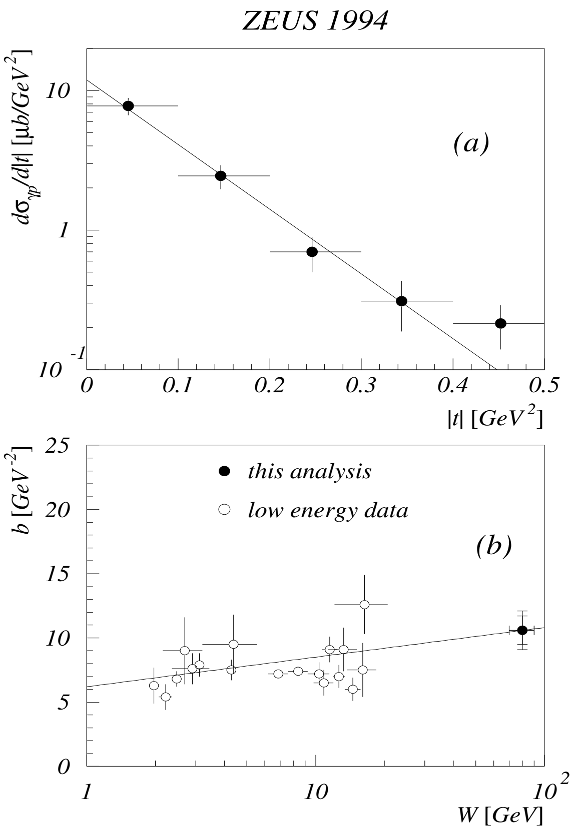
Examples of Soft Scale Reactions:

- Light Vector Meson production at $Q^2 = 0$.

VDM+Regge predictions

- **increase of the slope parameter 'b' with respect of lower energy results (shrinkage):**

$$\mathbf{b(W_{\gamma p}) = b_0 + 2\alpha'_{I\!P} ln(W^2_{\gamma p})}$$



$\gamma p \rightarrow \omega p$

$$\frac{d\sigma}{dt} = Ae^{-b|t|}$$

$A = 11.9 \pm 2.3 \pm 2.1$ **μb/GeV^2**

$b = 10.6 \pm 1.1 \pm 1.4$ **GeV^{-2}**

The line is the Regge dependence

$b = b_\circ + 2\alpha'_{I\!P} \ln W^2_{\gamma p} \quad (\alpha'_{I\!P} = 0.25)$

Norm. fixed on the HERA point.

- **cross section behavior with W:**

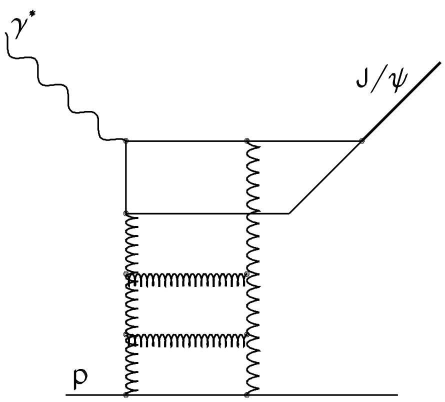
$$\sigma_{\gamma p \rightarrow Vp}(\mathbf{W_{\gamma p}}) \simeq \frac{\mathbf{W^{4\epsilon}_{\gamma p}}}{\mathbf{b(W_{\gamma p})}} \propto \mathbf{W^{0.22}_{\gamma p}}$$

$(\alpha_{I\!P}(t=0) = 1 + \epsilon = 1.08$ **from fit)**

W dependence in soft and hard processes

- Elastic J/ψ production at $Q^2 \geq 0$ GeV^2
- light meson at large Q^2

Described by pQCD models with $W_{\gamma p}$ dependence coupled to the low-x behavior of the proton gluon density $xg(x, Q^2)$



J/Ψ case:(Ryskin, 1993)

$\rightarrow$ $I\!P$ as a gluon ladder

$\rightarrow$ $\sigma \propto [\alpha_s(\bar{q}^2)\bar{x}g(\bar{x}, \bar{q}^2)]^2$, with

$$\bar{q}^2 = \frac{Q^2 + m^2_{J/\psi} + |t|}{4} \simeq 2.5 \text{ GeV}^2$$

$$\bar{x} = \frac{Q^2 + m^2_{J/\psi} + |t|}{W^2_{\gamma p}} \simeq 5 \cdot 10^{-4} \rightarrow 6 \cdot 10^{-3}$$

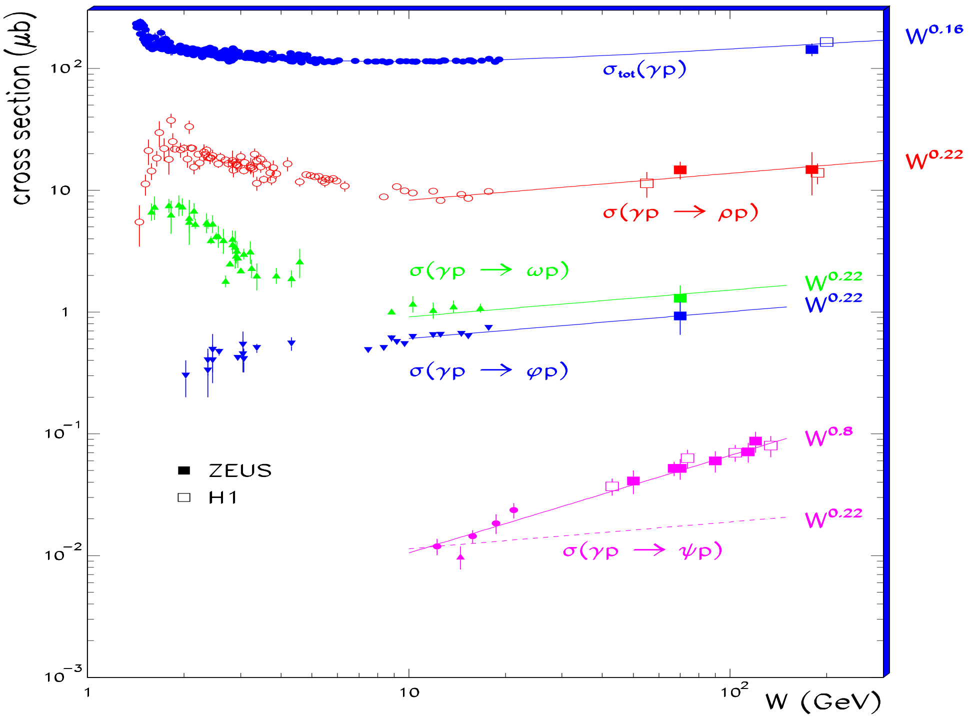
and corrections

$\rightarrow$ J/ψ relativistic wave function

$\rightarrow$ gluon $k_\perp$

$\rightarrow$ rescattering or absorption of $c\bar{c}$

Sensitivity to the gluon distribution



pQCD: the Skewed Parton Distribution

If in the final state a large mass is present, then the fractional momentum carried by the two gluons is different:

$$x_1 - x_2 = \Delta x = \frac{M_V^2 + Q^2}{W^2 + Q^2}$$

In this condition, what is measured is the skewed parton distribution (SPD), also called off-diagonal or non-forward parton distribution

$$xg(x, Q^2) \rightarrow xg(x_1, x_2, Q^2)$$

Skewed parton distributions are a generalization of normal parton distribution and give additional information on the non-perturbative parton distribution

Skewed parton distributions are larger than parton distributions:

$$\frac{\mathbf{x_2 g(x_1, x_2, Q^2)}}{\mathbf{xg(x, Q^2)}} \sim \mathbf{2}$$

and the cross section for these processes is enhanced.

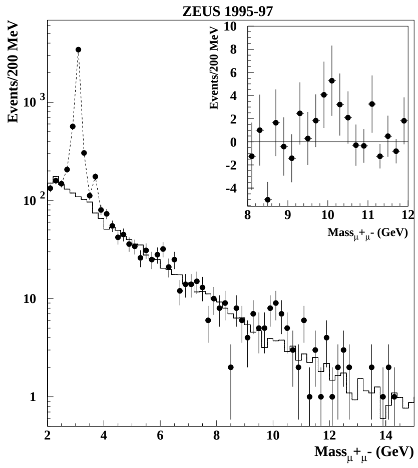
$\rightarrow \Upsilon$ production and Deeply Virtual Compton Scattering

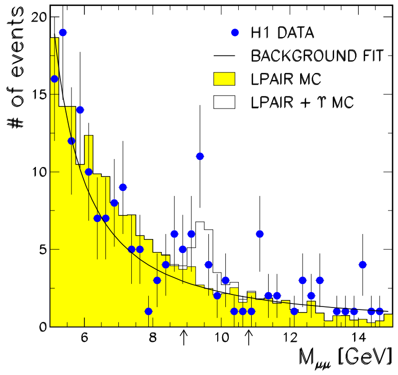
Diffractive Υ production

Need for Skewed Parton Distribution!

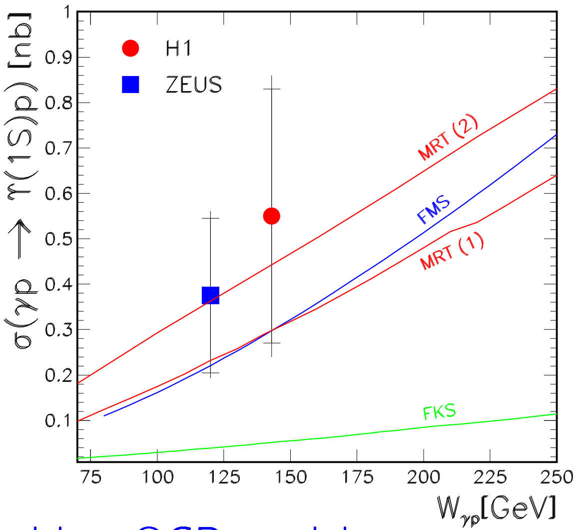
Elastic Υ Photoproduction

ZEUS $\int\mathcal{L} \simeq 43\ pb^{-1}$ H1 $\int\mathcal{L} \simeq 27\ pb^{-1}$





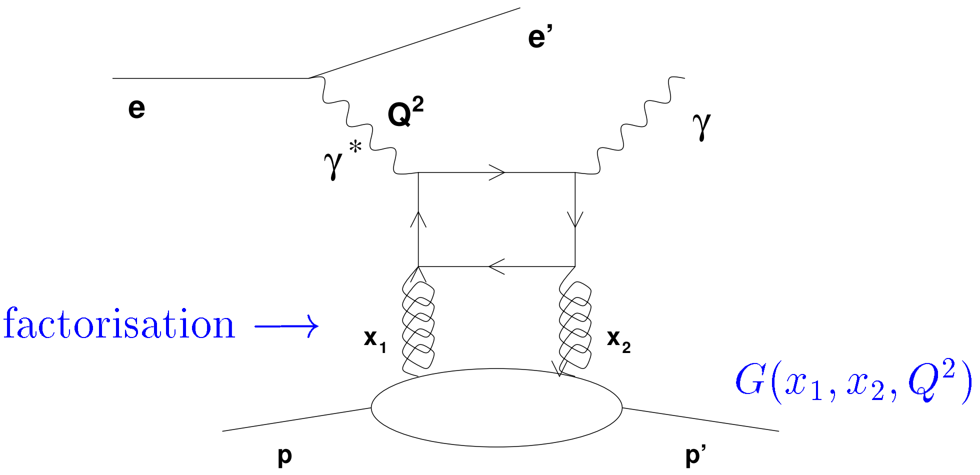
- $\Upsilon(1S), \Upsilon(2S), \Upsilon(3S)$ cannot be resolved
- Observed mass spectrum consistent with $\simeq 70\%$ contribution from $\Upsilon(1S)$ as observed elsewhere
- ZEUS: 17.1 ± 7.5 events, H1: 12.2 ± 6.3 events



▶ Described by pQCD models

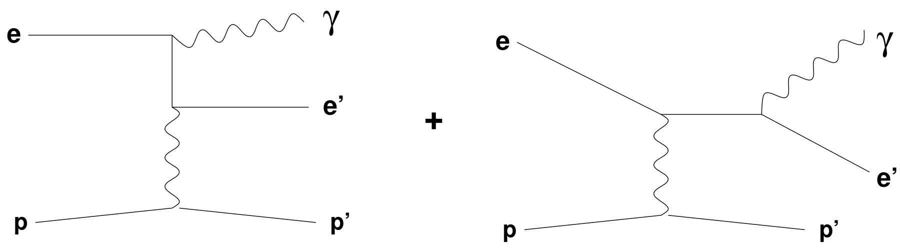
Deeply Virtual Compton Scattering (DVCS)

- QCD interpretation of DVCS process



$\Rightarrow$ Fully calculable in pQCD (no VM wave function)

- Bethe-Heitler process



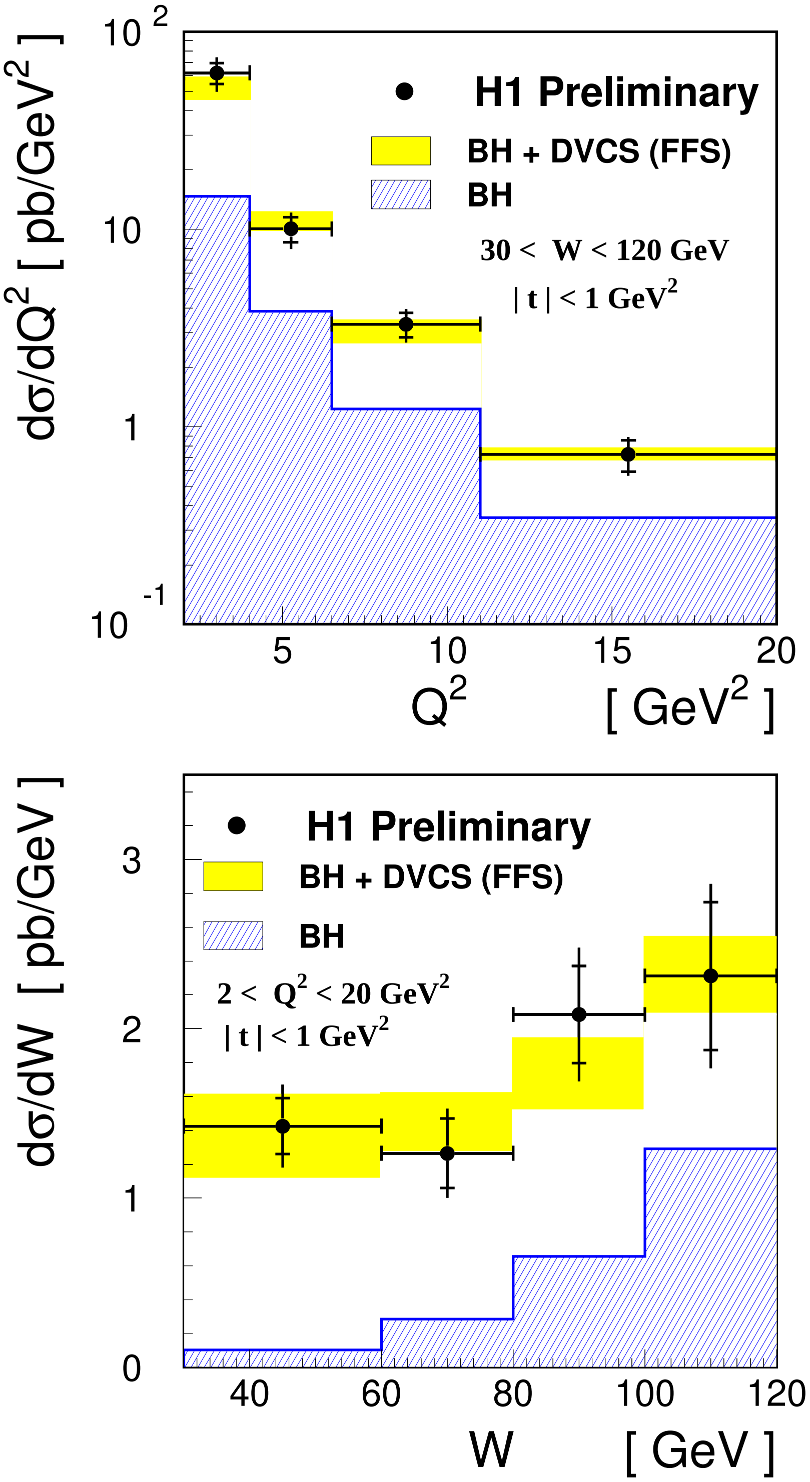
$\Rightarrow$ Direct contribution + interference

- QCD calculation by L. Franfurt, A. Freund and M. Strikman (FFS)
  A. V. Belitsky, D. Müller, L. Niedermeier and
  A. Schäfer
- Implemented in two independent MC for H1 and ZEUS
- access to real part of the QCD amplitude

$\Rightarrow$ access to skewed parton distributions

Deeply Virtual Compton Scattering (DVCS)

H1 Cross section measurement (Cont.)



Large Q^2 : restoration of SU(4) symmetry

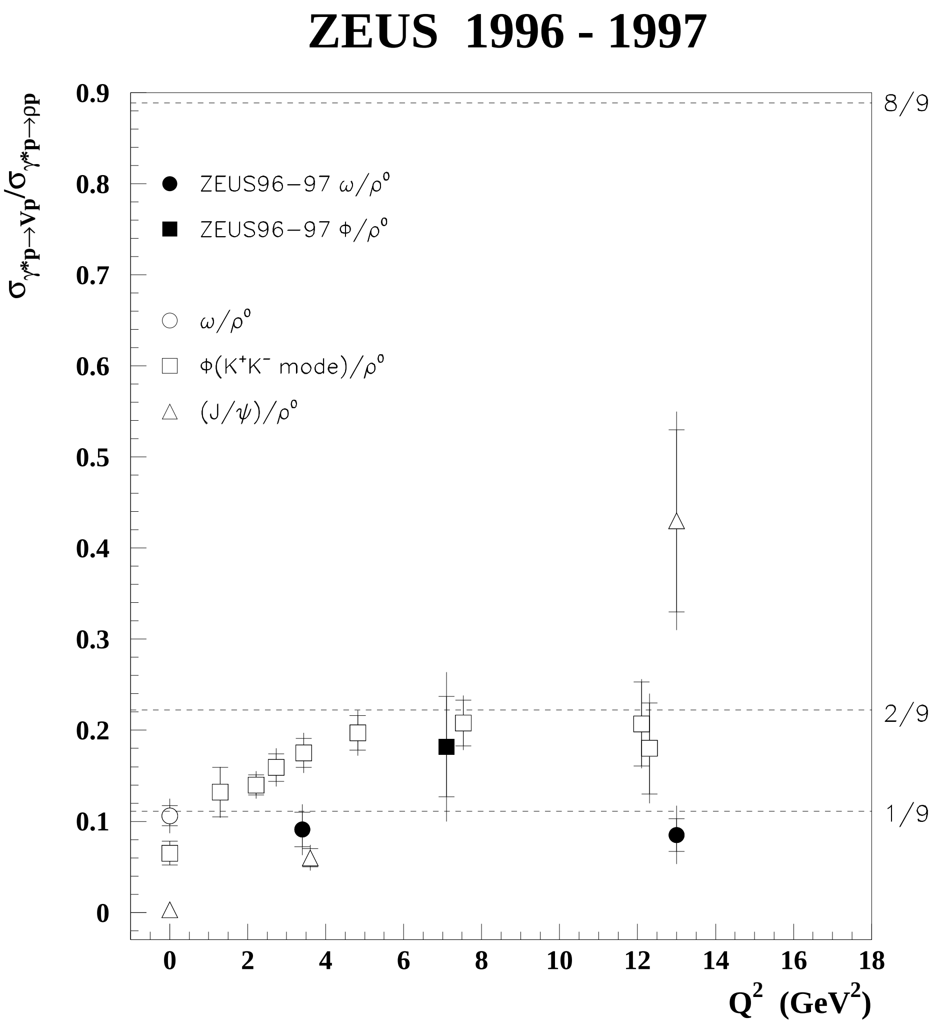
According to SU(4), when $m_q^2 << Q^2$, the ratio among cross sections should depend only on the mesons wavefunction:

$$\rho : \omega : \phi : \mathbf{J/\Psi} = [\frac{1}{\sqrt{2}}(u\bar{u}+d\bar{d})]^2 : [\frac{1}{\sqrt{2}}(u\bar{u}-d\bar{d})]^2 : [s\bar{s}]^2 : [c\bar{c}]^2 = 9 : 1 : 2 : 8$$

QCD dynamics $\Rightarrow$ enhancement of ϕ and J/Ψ:

$$\rho : \omega : \phi : \mathbf{J/\Psi} = 9 : (1 * 0.8) : (2 * 1.2) : (8 * 3.5)$$

At $Q^2 \sim 0.GeV^2$, this symmetry is badly broken but the HERA data at large Q^2 show a dramatic increase of both the ϕ and J/Ψ cross section



‘b’ values in hard processes

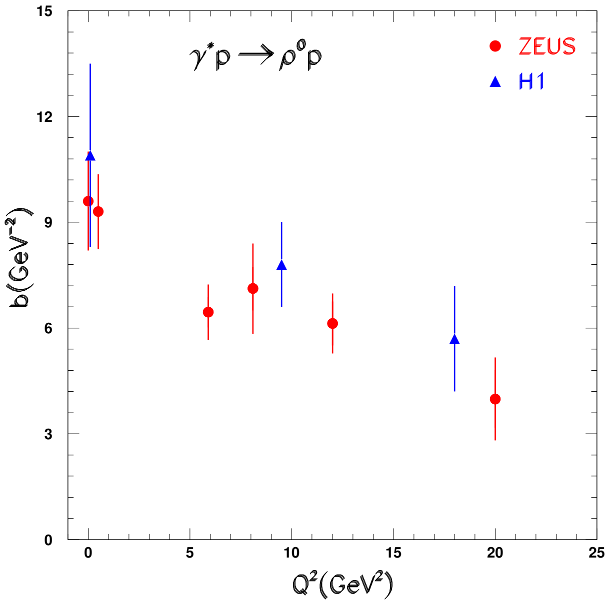
‘b’ vs Q^2:

b is related to the interaction radius:

$\mathbf{b} \sim \frac{1}{4}\mathbf{R}^2$ **with** $\mathbf{R}^2 = \sqrt{\mathbf{r_p^2} + \mathbf{r_\perp^2}}$

Soft physiscs $\sim$ **10 Ge**V^2

Hard physiscs $\sim$ **5 Ge**V^2



α' in hard processes:

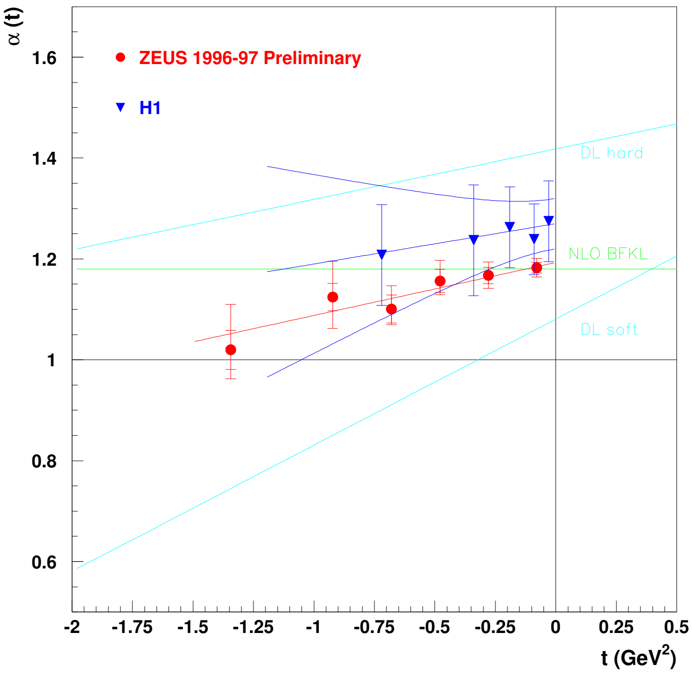
Soft physics: $\alpha' = 0.25 \rightarrow$

$b = b_o + 4\alpha' ln(W)$ **The peak shrinks with W,**

pQCD: $\alpha' \sim 0 \rightarrow$ **no shrinkage**

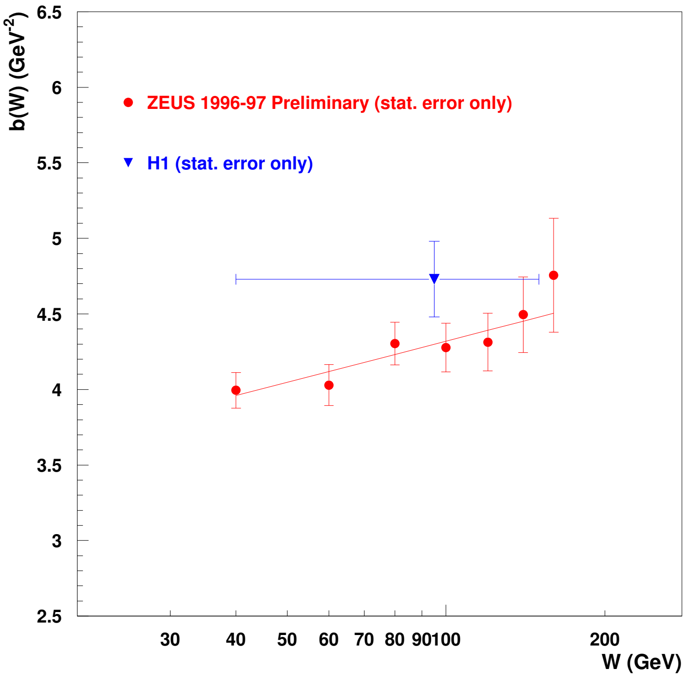
$\alpha = \alpha_o + \alpha' \cdot t$

$\alpha' = 0.098 \pm 0.035$



$b = b_o + 4\alpha' ln(W)$

$\alpha' = 0.105 \pm 0.024$



Summary on Vector meson production:

A large amount of data is now available from HERA

- Light vector mesons at low Q^2 show a behavior compatible with VDM:
  - Slow rise of the cross section with W
  - Increase of 'b' compatible with shrinkage.
- Very good success of pQCD in explaining non trivial issues:
  - Fast rise of the cross section with W
  - Lower 'b' value
  - Absence of shrinkage
  - SU(4) flavor symmetry restored
  - Existence of DVCS
  - Skewed parton distribution

Summary and Outlook:

A large amount of data is now available from HERA and TEVATRON

- Expandend understanding of QCD dynamics allow for precise predictions
- Diffraction allows to map the transition from non-perturbative to perturbative regimes
- The idea of "one pomeron fits all" has been proven wrong:
  - HERA and TEVATRON F_2^D are different both in shape and normalization,
  - HERA: Diffractive DIS = 10% Non Diffractive DIS
  - TEVATRON: Diffractive $W, b\bar{b}\ dijet$ = 1% Non Diffractive
  - TEVATRON data show factorization breaking in event with gaps and Double pomeron exchange
- Vector meson production is a key tool to understand pQCD prediction on diffraction
- New data coming soon: H1, CDF, D0 will have roman pots,
- Even LHC, looking forward to the Spomeron